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(54) Title: CORRECTED PARAMETER CONTROL METHOD FOR A TWO-SHAFT GAS TURBINE

(57) Abstract: A corrected parameter control method for a two-shaft gas turbine, of the type in which the protection of the said turbine is provided by a first control loop which controls the opening of fuel valves to keep the gas temperature  $T_{fire}$  at the inlet to a first wheel of the said turbine and the fuel/air ratio  $F/A$  within specified limits: this control is provided in such a way that the exhaust temperature  $TX$  has values calculated by a linear approximation, in other words as the sum of a reference temperature  $TX_{base}$  to which are added corrections relating to a single environmental or operating parameter which differs from the reference parameter; a second control loop, which controls the opening of a valve (bleed valve) located between the outlet of the axial compressor and the atmosphere, controls the  $F/A$  ratio: this control is provided in such a way that the exhaust temperature has values calculated by a linear approximation.

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CORRECTED PARAMETER CONTROL METHOD FOR A TWO-SHAFT GAS  
TURBINE

The present invention relates to a corrected parameter control method for a two-shaft gas turbine.

5 As is known, a two-shaft gas turbine is a machine consisting of a compressor, one or more combustion chambers, and two turbine wheels with one or more stages; one turbine wheel is connected by a shaft to the compressor, while the other wheel is connected to  
10 the load by the second shaft.

Air taken from the external environment is fed to the compressor to be pressurized. The compressor can be provided with suitable vent valves, also known as bleed valves, which discharge some of the compressed air to  
15 the atmosphere.

The pressurized air passes over the outside of the combustion chamber jackets, thus cooling them, and then reaches a set of burners which have the function of mixing the air and the fuel gas (obtained from external  
20 pipes), thus providing a gas-air mixture for burning. The pre-mixing of the air with the gas enables the local temperature to be contained in the following primary combustion region, thus limiting the formation

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of pollutants such as nitrogen oxides.

The combustion reaction takes place inside the jackets, where the temperature and consequently the enthalpy of the gases are increased.

- 5 The gas at high temperature and high pressure then passes through suitable pipes to the different stages of the turbine, which converts the enthalpy of the gas to mechanical energy available to a user.

It is known that, in order to obtain the maximum  
10 efficiency of any given gas turbine, the temperature of the gas at the inlet to the first turbine wheel, referred to below as the temperature  $T_{\text{Fire}}$ , must be as high as possible; however, the maximum temperatures that can be reached during the use of the turbine are  
15 limited by the strength of the materials used.

It is also known that, in order to obtain low emission of pollutants, the fuel-air ratio (abbreviated to  $F/A$  in the following text) must be suitably controlled; however, the acceptable values of  $F/A$  are limited by  
20 problems of loss of ignition in the gas turbine or the generation of pressure pulsations in the combustion chamber.

In practice, there is a requirement to design a

thermodynamic cycle for the two-shaft gas turbine which will yield high efficiency combined with low emission of pollutants.

However, the nominal thermodynamic cycle of a gas turbine is modified in practical applications by disturbance factors such as:

- variations of environmental conditions (pressure, temperature and humidity);
- variations of pressure drops in the inlet air intake pipes;
- variations of the pressure drops in the exhaust gas discharge pipes;
- variations of the speed of the low pressure shaft (connected to the user).

If due allowance is not made for these disturbance factors, they may have the following effects:

- failure to achieve the maximum temperature  $T_{Fire}$  at the inlet of the first turbine wheel in full load conditions (with consequent reduction of the thermodynamic performance of the turbine);
- exceeding of the maximum temperature  $T_{Fire}$  at the inlet of the first turbine wheel in full load conditions, with consequent reduction of the

maintenance interval for the turbine;

- failure to achieve the correct fuel-air ratio  $F/A$  in the combustion chamber with a consequent increase in the emission of pollutants such as nitrogen oxides (also abbreviated to  $NO_x$  in the following text) and carbon monoxide, and the appearance of dangerous pressure pulsations in the combustion chamber or loss of ignition in the combustion chamber.

The object of the present invention is therefore to provide a method for controlling  $T_{Fire}$  and  $F/A$  which can overcome the aforementioned problems, particularly by proposing a corrected parameter control method for a two-shaft gas turbine which enables high machine efficiency to be achieved together with low emission of pollutants.

Another object of the present invention is to propose a corrected parameter control method for a two-shaft gas turbine which is reliable and is applied by means of simple relations which are easily implemented on the control panels of the machine.

These and other objects of the present invention are achieved by proposing a corrected parameter control method for a two-shaft gas turbine as disclosed in

Claim 1.

Further characteristics of the corrected parameter control method for a two-shaft gas turbine are specified in the subsequent claims.

5 The characteristics and advantages of a corrected parameter control method for a two-shaft gas turbine according to the present invention will be made clearer by the following description, provided by way of example and without restrictive intent, which refers to  
10 the attached schematic drawings in which:

Figure 1 shows a correlation between the exhaust temperature TX and the compression ratio PR relating to operating conditions in which the machine has reached the limit value of TFire or F/A in standard conditions,  
15 in other words where the speed of the low pressure wheel is 100%, the pressure drops are zero in the intake and exhaust pipes and the relative humidity is 60%; this curve shows the maximum permissible exhaust temperature for the gas turbine;

20 Figure 2 shows two curves of the maximum exhaust temperature in standard operating conditions: the first curve 21 represents the curve of maximum exhaust temperature due to the attainment of the limit value of

TFire; the second curve 23 represents the curve of maximum exhaust temperature due to the attainment of the limit value of  $F/A$ ;

Figure 3 shows how the curve of maximum exhaust  
5 temperature due to the limit value of TFire is modified by the variation of the speed of the low pressure wheel;

Figure 4 shows how the curve of maximum exhaust temperature due to the limit value of  $F/A$  is modified  
10 by the variation of the speed of the low pressure wheel;

Figure 5 is a diagram of the correlation between the variation of maximum exhaust temperature due to a variation of the environmental humidity with respect to  
15 the standard value of 60%;

Figure 6 shows the correlation between the variation of maximum exhaust temperature and the variation of the pressure drops in the inlet pipes with respect to the standard value of 0 mm of water (abbreviated to 0  
20 mmH<sub>2</sub>O);

Figure 7 shows the correlation between the variation of maximum exhaust temperature and the variation of the pressure drops in the exhaust pipes with respect to the

standard value of 0 mmH<sub>2</sub>O;

Figure 8 shows a correlation between the exhaust temperature TX and the compression ratio PR and the ambient temperature (used as an independent parameter) relative to operating conditions in which the machine has reached the nominal value of F/A in standard conditions, in other words with a low pressure wheel speed of 100%, zero pressure drops in the intake and exhaust pipes and relative humidity of 60%; this curve represents the desired exhaust temperature for achieving the nominal value of F/A;

Figure 9 is derived from Figure 8 by nondimensionalizing it with respect to ambient temperature;

Figure 10 shows the set of nondimensionalized curves (as in Figure 9) relating to different speeds of the low pressure wheel;

Figure 11 shows the correlation between the variation of the exhaust temperature required to achieve the nominal F/A and the variation of the environmental humidity with respect to the standard value of 60%;

Figure 12 shows the correlation between the variation of exhaust temperature required to achieve nominal F/A



and the variation of the pressure drops in the intake pipes with respect to the standard value of 0 mmH<sub>2</sub>O;

Figure 13 shows the correlation between the variation of exhaust temperature required to achieve nominal F/A  
5 and the variation of the pressure drops in the exhaust pipes with respect to the standard value of 0 mmH<sub>2</sub>O.

With reference to the figures, a corrected parameter control method for a two-shaft gas turbine is indicated.

10 The control system consists of two feedback control loops by means of which the following actions are carried out independently:

1. First loop: protection of the machine by limiting the opening of the fuel valves to keep T<sub>Fire</sub> and  
15 F/A within specified limits;
2. Second loop: control of F/A by controlling the opening of the bleed valve.

We shall start with a discussion of the control loop for protecting the machine from high values of T<sub>Fire</sub> or  
20 F/A.

The limit operating conditions at full load are encountered when one of the following cases is present:

- the maximum fuel to air ratio F/A is reached in

the combustion chamber, in other words there is a maximum temperature increment  $T_{rise}$  of the gases in the combustion chamber;

- the maximum temperature  $T_{Fire}$  is present.

5 These limits can be expressed in the form of a curve on a plane  $PR - TX$ , in other words a curve showing the exhaust temperature  $TX$  as a function of the compression ratio  $PR$  of the axial compressor: when conditions on this curve are reached, the flow of fuel is reduced, so  
10 that the curve represents a curve of maximum permissible exhaust temperature.

Figure 1 shows a diagram of an example of a curve of maximum permissible exhaust temperature  $TX$ , expressed in degrees Rankine, at 100% of the load speed (in other  
15 words the speed of the low pressure shaft to which the load is applied) with pressure drops of 0 mmH<sub>2</sub>O at the intake and exhaust and 60% relative humidity, as a function of the compression ratio  $PR$ .

More precisely, the curve in the diagram of Figure 1  
20 has three zones.

For low compression ratios  $PR$ , there is a horizontal zone 11 of maximum exhaust temperature  $TX$ , due to limits on the materials of the exhaust pipe. As the

compression ratio PR increases, the curve descends with a zone 13 where the limit due to the maximum TFire is applicable.

The curve continues with a zone 15 where the limit of maximum Trise is the determining factor, and the temperature TX decreases further as the compression ratio PR increases.

Figure 2 shows two curves of maximum permissible exhaust temperature TX, as functions of the compression ratio PR.

More precisely, there is a curve 21 related to the maximum temperature TFire and a curve 23 related to the maximum Trise. The two curves 21 and 23 have a trend which is linear to a first approximation, with a negative slope; in particular, the two curves intersect at 25.

The control curve for the actual temperature TX is determined by selecting the minimum temperature TX from the curves 21 and 23, for each compression ratio PR.

Thus at low compression ratios PR the maximum TFire is the determining factor, while the limit of maximum Trise becomes decisive from the intersection 25 onwards.

The curve 21 related to the maximum TFire protects the machine from damage caused by excess temperatures due to overheating, and is always active.

On the other hand, the curve 23 depends on the maximum  
5 permissible F/A ratio, and therefore on the maximum Trise, and can be modified to meet the specific requirements of the combustion system.

It is therefore useful to have the two curves 21 and 23 additionally available in two separate diagrams, so  
10 that two different reference points or set points can be established for the TX controller of the fuel control loop. A minimum selector will select the appropriate set point of exhaust temperature TX, by selecting the minimum from the values of TX obtained by  
15 entering the curve 21 and the curve 23 with the compression ratio PR.

Ultimately, each environmental condition and each load characteristic on the low pressure shaft requires a specific temperature control curve.

20 In order to take the different situations into account, the corrected parameter control method for a two-shaft gas turbine is implemented according to the following formula, in order to ensure that the gas turbine is

always in an ideal configuration:

$$TX = TX_{base} + \Delta TX_{DPin} + \Delta TX_{DPout} + \Delta TX_{Hum} + \Delta TX_{PCNLP}$$

Clearly, a linear approximation is provided, in which:

- 5 -  $TX_{base}$  is the maximum exhaust temperature obtained at 100% of rotation speed of the low pressure shaft, pressure drops of 0 mmH<sub>2</sub>O in the exhaust and intake pipes and 60% relative humidity reference temperature (see Figure 1); this is equivalent to the minimum value  
10 of  $TX$  found for the same PR from the curves 21 and 23 of Figure 2;
- $\Delta TX_{Dpin}$  is the correction of the temperature  $TX$  due to the variation of the pressure drops in the intake pipes with respect to the nominal value of 0  
15 mmH<sub>2</sub>O (see Figure 6);
- $\Delta TX_{Dpout}$  is the correction of the temperature  $TX$  due to the variation of the pressure drops in the exhaust pipes with respect to the nominal value of 0 mmH<sub>2</sub>O (see Figure 7);
- 20 -  $\Delta TX_{Hum}$  is the correction of the temperature  $TX$  due to the variation of the relative humidity of the air with respect to the nominal value of 60% (see Figure 5);

- DeltaTX\_PCNLP is the correction of the temperature TX due to the variation of the speed of the low pressure shaft with respect to the nominal value of 100%; this parameter is found as the difference between  
5 TXbase and the minimum value of TX found for the same PR from the curves of Figures 3 and 4.

In the above equation, therefore, the exhaust temperature TX is derived from a reference temperature TXbase, to which are added four corrections called  
10 DeltaTX\_Dpin, DeltaTX\_Dpout, DeltaTX\_Hum and DeltaTX\_PCNLP.

Each correction term relates to a single environmental or operating parameter which differs from the reference parameter, and is calculated by computer simulations of  
15 the gas turbine. The simulations are generated by setting the attainment of the maximum permissible temperatures Tfire or Trise, for each condition differing from the reference condition.

The exhaust temperature TX found by the above  
20 simulations is compared with the reference temperature TXbase, so that the correction terms can be evaluated appropriately as differences.

Since two control curves 21 and 23 have been defined,

two temperatures TXbase are provided, and each correction term has to be added to both.

We will now describe the method of evaluating DeltaTX\_PCNLP, in other words the exhaust temperature  
5 correction term due to differences between the speed of the low pressure turbine (to which the load is applied) and the reference speed.

The speed of the low pressure turbine is the most important parameter for the correction of the exhaust  
10 temperature TX, since it acts directly on the efficiency of the low pressure turbine and therefore also on Tfire.

So that this importance can be taken into account, a maximum exhaust temperature curve is generated for each  
15 speed considered.

The equation for evaluating the current exhaust temperature TX then becomes somewhat different from that stated above, in other words

$$\begin{aligned} \text{TX} &= \text{TXbase}(\text{PCNLP}) + \text{DeltaTX\_DPin} + \text{DeltaTX\_Dpout} \\ 20 \quad &+ \text{DeltaTX\_Hum} \end{aligned}$$

where TXbase(PCNLP) is the reference temperature found for the specific speed of the low pressure turbine.

Clearly, there will be two values of TXbase(PCNLP):

this is because there is a curve 21 for the maximum temperature  $T_{fire}$  and a curve 23 for the maximum permissible  $Trise$ . Thus the following formulae are required, with additional allowance for the dependence  
 5 of the base curves on the compression ratio  $PR$ :

$$\begin{aligned} TX\_maxT_{fire} &= TXbase\_maxT_{fire}(PCNLP, PR) + \\ &\Delta TX\_DPin + \Delta TX\_Dpout + \Delta TX\_Hum \\ TX\_maxTrise &= TXbase\_maxTrise(PCNLP, PR) + \\ &\Delta TX\_DPin + \Delta TX\_Dpout + \Delta TX\_Hum. \end{aligned}$$

10 Both of the temperature curves  $TXbase\_maxT_{fire}$  and  $TXbase\_maxTrise$  can also be provided in the form of two-dimensional tables, since there are two independent variables, namely the compression ratio  $PR$  and the low pressure turbine speed  $PCNLP$ .

15 Figure 3 shows a diagram of the maximum temperature  $TX$ , expressed in degrees Rankine, as a function of the compression ratio  $PR$ , which enables the maximum  $T_{fire}$  to be attained. It shows a set of curves 27, each for a specific value of speed  $PCNLP$ . More precisely, as this  
 20 speed increases, the curve 27 generally has an increasingly negative slope, and is always of the type decreasing with a rise in the compression ratio  $PR$ .

Figure 4 shows a diagram of the maximum temperature  $TX$ ,



expressed in degrees Rankine, as a function of the compression ratio PR, which enables the maximum Trise to be attained. It shows a set of curves 29, each for a specific value of speed PCNLP. More precisely, as this  
5 speed increases, the curve 29 generally has an increasingly negative slope, and is always of the type decreasing with a rise in the compression ratio PR.

We will now describe the method of evaluating the term DeltaTX\_Hum, in other words the correction of  
10 temperature TX which allows for the environmental humidity.

In fact, the significant parameter for characterizing atmospheric humidity is not the relative humidity (RH), which also depends on the temperature and on  
15 atmospheric pressure, but specific humidity (SH) which is the absolute water content of the atmosphere.

Additionally, according to current practice, the curves of maximum exhaust temperature TX are found by assuming a constant relative humidity of 60%.

20 For these two reasons, the most convenient parameter for expressing the moisture content of the air appears to be the difference DeltaSH, defined as the difference between the actual specific humidity and the specific

humidity at a relative humidity of 60% (in the same conditions of temperature and atmospheric pressure), according to the formula:

$$\text{DeltaSH} = \text{SH\_current} - \text{SH\_60\%RH}.$$

- 5 When DeltaTX\_Hum is plotted on a diagram as a function of DeltaSH, a linear correlation appears between these two variables.

Therefore, in order to implement the correction due to atmospheric humidity in the corrected parameter control  
10 method for a two-shaft gas turbine according to the invention, it is necessary to use two correlations, namely:

- DeltaTX\_Hum as a function of DeltaSH which is shown in Figure 5;
- 15 - SH\_60%RH as a function of atmospheric temperature, which can be found by interpolating the following values, where the temperature is expressed in degrees Rankine:

- SH\_60%RH (T=419.67) = 0.000070;
- 20 SH\_60%RH (T=428.67) = 0.000116;
- SH\_60%RH (T=437.67) = 0.000188;
- SH\_60%RH (T=446.67) = 0.000299;

SH\_60%RH (T=455.67) = 0.000464;  
 SH\_60%RH (T=464.67) = 0.000707;  
 SH\_60%RH (T=473.67) = 0.001059;  
 SH\_60%RH (T=482.67) = 0.001560;  
 5 SH\_60%RH (T=491.67) = 0.002263;  
 SH\_60%RH (T=500.67) = 0.003324;  
 SH\_60%RH (T=509.67) = 0.004657;  
 SH\_60%RH (T=518.67) = 0.006367;  
 SH\_60%RH (T=527.67) = 0.008670;  
 10 SH\_60%RH (T=536.67) = 0.011790;  
 SH\_60%RH (T=545.67) = 0.015966;  
 SH\_60%RH (T=554.67) = 0.021456;  
 SH\_60%RH (T=563.67) = 0.028552;  
 SH\_60%RH (T=572.67) = 0.037585;  
 15 SH\_60%RH (T=581.67) = 0.048949.

Figure 5 shows the linear correlation, shown by the straight line 31, between DeltaTX\_Hum, expressed in degrees Rankine, and DeltaSH.

We will now describe the parameter DeltaTX\_Dpin, in  
 20 other words the correction of temperature due to the pressure drop in the intake pipes.

Since a value of zero, in other words no drop, has been chosen as the reference for the drops in the intake pipes, the correction  $\Delta T_{X\_Dpin}$  can be expressed directly as a function of the measured pressure drop  
5  $D_{Pin}$ .

By conducting various simulations, for which the attainment of  $\max T_{fire}$  or  $\max T_{rise}$  with pressure drops different from zero had been specified, it was found that there was a correlation between  $D_{Pin}$  and  
10  $\Delta T_{X\_Dpin}$ . This correlation is linear to a first approximation and is shown in Figure 6.

More precisely, Figure 6 shows the linear correlation, shown by the straight line 33, between  $\Delta T_{X\_Dpin}$ , expressed in degrees Rankine, and  $D_{Pin}$ , expressed in mm  
15 of water.

We will now examine  $\Delta T_{X\_Dpout}$ , in other words the correction of temperature due to the pressure drop in the exhaust pipes.

Since a value of zero, in other words no drop, has been  
20 chosen as the reference for the drops in the intake pipes, the correction  $\Delta T_{X\_Dpout}$  can be expressed directly as a function of the measured pressure drop  $D_{Pout}$ .

By conducting various simulations, for which the attainment of max Tfire or max Trise with pressure drops different from zero had been specified, it was found that there was a correlation between Dpout and  
5 DeltaTX\_Dpout. This correlation is linear to a first approximation and is shown in Figure 7.

More precisely, Figure 7 shows the linear correlation, shown by the straight line 35, between DeltaTX\_Dpout, expressed in degrees Rankine, and Dpout, expressed in  
10 mm of water.

2<sup>nd</sup> loop: we will now describe the control loop for controlling F/A (and consequently Trise) by controlling the opening of the bleed valve at partial loads. This valve is located between the atmosphere and the outlet  
15 of the axial compressor. The set point of the control loop controller is obtained from a set of TX-PR maps obtained for all operating conditions of the machine.

For each environmental condition, there is an infinite number of curves of exhaust temperature TX for  
20 attaining the nominal F/A (or nominal Trise): in particular, if other conditions remain constant, it is possible to define a control curve for each value of atmospheric temperature.

Figure 8 shows a diagram of the maximum temperature TX for partial loads at a given speed of the low pressure shaft, expressed in degrees Rankine, as a function of the compression ratio PR. It shows a set of curves 37, each for a given value of atmospheric temperature. More precisely, as this temperature rises the curve 37 generally takes higher values, while always being of the type which decreases as the compression ratio PR increases.

According to the present invention, a corrected parameter method is used, in which all the aforementioned curves 37 are reduced to a single curve 39, shown in Figure 9, to eliminate the dependence on the atmospheric temperature.

The curve 39 is obtained by the following mathematical transformation:

$$TTX = TX \cdot (518.67/TCD)^x$$

where

- TX is the actual exhaust temperature;
- 518.67 is a reference temperature which in this case is expressed in degrees Rankine;
- TCD is the exhaust temperature of the compressor, expressed in a unit of measurement

compatible with that of the constant, and therefore in degrees Rankine in this case;

- X is a nondimensional exponent calculated in such a way as to minimize the mean quadratic deviation between the values of TTX calculated in  
5 this way and the interpolation curve 39;

- TTX is the exhaust temperature transformed by the preceding relation, referred to hereafter as the reduced temperature.

10 When the actual value of PR is known, and after application of the inverse of the above transformation, the curve 39 yields the set point for the TX controller of the control loop for F/A (and consequently for Trise).

15 Using the curve 39 makes it unnecessary to enter the large number of points which would be required to describe all the curves 37 of Figure 8.

Even if the dependence on atmospheric temperature is removed, the curve of temperature TX for partial loads  
20 depends on the following conditions:

- pressure drop in the intake pipes;
- pressure drop in the exhaust pipes;
- atmospheric humidity;

- load characteristics (for example, by correlation between load and speed).

In a similar way to what has been described above in relation to the maximum exhaust temperature curve, the  
5 corrected parameter control method for gas turbines makes it possible to take into account operating conditions differing from the design conditions for the case of partial load control curves.

This is expressed by the formula:

$$10 \quad TX = TX_{base} + \Delta TX_{DPin} + \Delta TX_{Dpout} + \Delta TX_{RH} + \Delta TX_{PCNLP}$$

where  $TX_{base}$  is obtained by inverting the formula given previously, thus:

$$TX_{base} = TTX / ((518.67/TCD)^X).$$

15 Each term of the above equation represents a correction to the reference temperature curve which takes the aforementioned parameters into consideration.

Each correction term is calculated by computer simulations of the gas turbine. The simulations are  
20 conducted by specifying the attainment of the desired F/A ratio (and consequently the attainment of the desired Trise), for each condition differing from the reference condition and at different partial loads.



The exhaust temperature TX found by the preceding simulations is compared with the reference temperature TXbase, in order to evaluate the correction terms in the appropriate way as differences.

- 5 We will now describe the method of evaluating the term DeltaTX\_PCNLP, in other words the correction of exhaust temperature due to the speed of the low pressure turbine to which the load is applied.

As stated previously, the low pressure turbine speed is  
10 the most important parameter for the correction of the exhaust temperature TX, since it acts directly on the efficiency of the low pressure turbine and therefore also on Tfire.

To take this importance into account, a partial load  
15 exhaust temperature curve is generated for each speed considered.

The equation for evaluating the current exhaust temperature TX therefore becomes somewhat different from that given above, thus:

20 
$$TX = TXbase(PCNLP) + DeltaTX\_DPin + DeltaTX\_Dpout + DeltaTX\_RH$$

where TXbase(PCNLP) is the reference temperature found for the specific speed of the low pressure turbine.

Figure 10 shows a diagram of the reduced temperature TTX, expressed in degrees Rankine, as a function of the compression ratio PR. It shows a set of curves 41, one for each given value of speed PCNLP. To find the true value of the parameter TXbase, the value of the exponent X must be known; this exponent is a function of the speed of the low pressure wheel, and typical values for a two-shaft turbine are given below by way of example:

10       if PCNLP = 105%, X = 0.323  
          if PCNLP = 100%, X = 0.33225  
          if PCNLP = 90%, X = 0.34  
          if PCNLP = 80%, X = 0.34425  
          if PCNLP = 70%, X = 0.351  
15       if PCNLP = 60%, X = 0.348  
          if PCNLP = 50%, X = 0.3505.

We will now describe the method of evaluating DeltaTX\_RH, in other words the correction of temperature due to environmental humidity.

20   The reference value of environmental humidity is 60%.  
The current value of the water content in the air (specific humidity) is not constant, but depends on the

atmospheric temperature.

To evaluate the effects of humidity in different conditions, the following were considered in the invention:

- 5    - three ambient temperatures (very cold day, ISO standard conditions, very hot day);
- three levels of relative humidity (0%, 60%, 100%);
- load characteristics according to a cubic law.

Thus nine simulations were conducted, specifying the  
10 attainment of the desired value of F/A and therefore of Trise, in order to achieve the reference level. The current values of TX were then plotted on a diagram as functions of PR.

The difference between the aforesaid diagram and the  
15 base curves yields DeltaTX\_RH; this is expressed as a formula thus:

$$\text{DeltaTX\_RH} = \text{TX} - \text{TXbase.}$$

The values of DeltaTX\_RH, expressed in degrees Rankine, are plotted in Figure 11 as a function of DeltaSH,  
20 where DeltaSH is defined as the difference between the current value of specific humidity SH\_current and the specific humidity at RH = 60%, SH\_60%RH, which is the reference value. This is expressed as a formula thus:

$$\text{DeltaSH} = \text{SH\_current} - \text{SH\_60\%RH}.$$

Figure 11 shows two straight lines 43 and 45, rising with an increase in DeltaSH, in which the straight line 43, valid where DeltaSH is less than 0, has a greater  
5 slope than the straight line 45, valid where DeltaSH is greater than 0, the two straight lines 43 and 45 passing through a point near the origin of the axes. For example, the point 44 on the straight line 43 indicates various partial loads at an ambient  
10 temperature of 50°C with RH = 0%; the point 46 on the straight line 45 indicates various partial loads at an ambient temperature of 50°C with RH = 100%.

More particularly, Figure 11 shows that:

- for a given DeltaSH, DeltaTX\_RH is practically  
15 independent of the load and thus also of the compression ratio PR (a maximum deviation of 3°F is observed at 50°C with an RH of 0%);

- DeltaTX\_TH is linearly proportional to DeltaSH, as shown by the two portions of straight line 43 and 45.

20 The relation between SH\_60%RH and the ambient temperature has already been described.

We will now describe the parameter DeltaTX\_Dpin, in other words the correction of exhaust temperature due

to the pressure drop in the intake pipes.

Since the value of zero, in other words no drop, was chosen as the reference for the pressure drops in the intake pipes, the correction  $\Delta TX_{Dpin}$  can be  
5 expressed directly as a function of the measured pressure drop  $DPin$ .

To calculate the effects of the pressure drop in the intake pipes in different conditions, the following were considered in the invention:

- 10 - three ambient temperatures (very cold day, ISO standard conditions, very hot day);
  - three pressure drops in the intake (0, 100 and 200 mm of water);
  - load characteristics according to a cubic law.
- 15 The pressure drops considered were appropriately decreased at a partial load.

Thus nine simulations were conducted, specifying the attainment of the desired value of  $F/A$ , and therefore of  $Trise$ , in order to achieve the reference level. The  
20 current values of  $TX$  were then plotted on a diagram as functions of  $PR$ .

The difference between the aforesaid diagram and the base curves yields  $\Delta TX_{Dpin}$ ; this is expressed as a

formula thus:

$$\text{DeltaTX\_Dpin} = \text{TX} - \text{TXbase}.$$

The values of DeltaTX\_Dpin, expressed in degrees Rankine, are plotted in Figure 12 as a function of  
5 Dpin.

Figure 12 shows a straight line 47, rising with an increase in Dpin, expressed in mm of water.

More particularly, Figure 12 shows that:

- for a given Dpin, the DeltaTX\_Dpin is practically  
10 independent of the load and thus also of the compression ratio PR (a maximum deviation of 2°F was observed);
- DeltaTX\_Dpin is linearly proportional to Dpin.

We will now describe the parameter DeltaTX\_Dpout, in  
15 other words the correction of temperature due to the pressure drop in the exhaust pipes.

Since the value of zero, in other words no drop, was chosen as the reference for the pressure drops in the exhaust pipes, the correction DeltaTX\_Dpout can be  
20 expressed directly as a function of the measured pressure drop DPout.

To calculate the effects of the pressure drop in the

exhaust pipes in different conditions, the following were considered in the invention:

- three ambient temperatures (very cold day, ISO standard conditions, very hot day);
- 5 - three pressure drops in the exhaust (0, 100 and 200 mm of water);
- load characteristics according to a cubic law.

The pressure drops considered were appropriately decreased at a partial load.

10 Thus nine simulations were conducted, specifying the attainment of the desired value of  $F/A$ , and therefore of  $Trise$ , in order to achieve the reference level. The current values of  $TX$  were then plotted on a diagram as functions of  $PR$ .

15 The difference between the aforesaid diagram and the base curves yields  $\Delta TX_{Dpout}$ ; this is expressed as a formula thus:

$$\Delta TX_{Dpout} = TX - TX_{base}.$$

The values of  $\Delta TX_{Dpout}$ , expressed in degrees  
20 Rankine, are plotted in Figure 13 as a function of  $Dpout$ .

Figure 13 shows a straight line 49, rising with an

increase in  $D_{pout}$ , expressed in mm of water.

In conclusion, in view of the above description, according to the corrected parameter control method for a two-shaft gas turbine according to the present invention, the correlation for calculating the maximum exhaust temperature TX is:

$$\begin{aligned} TX = & TTX(PCNLP, PR) / ((518.67/TCD)^{X(PCNLP)}) + \\ & \Delta TX_{RH} (\Delta SH) + \\ & \Delta TX_{Dpin} (Dpin) + \\ 10 \quad & \Delta TX_{Dpout} (Dpout). \end{aligned}$$

The method according to the present invention can be applied advantageously in a two-shaft gas turbine with a dry nitrogen oxide (NOx) reduction system (also called a Dry Low NOx or DLN system).

15 The characteristics and the advantages of the corrected parameter control method for a two-shaft gas turbine according to the present invention are made clear by the above description.

It should be emphasized, in particular, that the introduction of corrected parameters into the control of DLN two-shaft turbines makes it possible to correct and eliminate effects due to disturbance factors by means of simple relations which can be implemented



easily in existing control panels.

Finally, it is clear that the corrected parameter control method for a two-shaft gas turbine devised in this way can be modified and varied in numerous ways  
5 without departure from the invention; furthermore, all components can be replaced with equivalent elements or parameters.

The scope of protection of the invention is therefore delimited by the attached claims.

CLAIMS

1. Corrected parameter control method for a two-shaft gas turbine, characterized in that protection of the said turbine is provided by a first control loop which  
5 controls the opening of the fuel valves to keep the temperature  $T_{\text{fire}}$  of the gas at the inlet of the first wheel of the said turbine and the fuel-air ration  $F/A$  within specified limits; the said control is provided in such a way that the set-point exhaust temperature  $TX$   
10 is calculated as the sum of a reference temperature  $TX_{\text{base}}$  to which are added corrections relating to a single environmental or operating parameter which differs from the reference parameter.

2. Control method according to Claim 1, characterized  
15 in that the said corrections are calculated by computer simulations of the said gas turbine, the said simulations being conducted by specifying the attainment of a maximum of the said temperature  $T_{\text{fire}}$  or a maximum of the said fuel-air ratio  $F/A$ , for each  
20 condition differing from the reference condition.

3. Control method according to Claim 1, characterized in that there are four of the said corrections, the said exhaust temperature  $TX$  being expressed by the following formula:

$$\text{TX} = \text{TXbase} + \text{DeltaTX\_DPin} + \text{DeltaTX\_DPout} + \text{DeltaTX\_Hum} + \text{DeltaTX\_PCNLP}$$

where

DeltaTX\_Dpin is the correction of the temperature TX  
5 due to the variation of the pressure drops in intake pipes with respect to a nominal value of 0 mmH2O,

DeltaTX\_Dpout is the correction of the temperature TX due to the variation of the pressure drops in exhaust pipes with respect to a nominal value of 0 mmH2O,

10 DeltaTX\_Hum is the correction of the temperature TX due to the variation of the relative humidity of the air with respect to a nominal value of 60%,

DeltaTX\_PCNLP is the correction of the temperature TX due to the variation of the speed of the low pressure  
15 shaft with respect to a nominal value of 100%.

4. Control method according to Claim 2, characterized in that the said exhaust temperature TX found by the said simulations is compared with the said reference temperature TXbase, in order to evaluate the said  
20 correction terms appropriately, as differences.

5. Control method according to Claim 3, characterized in that a maximum exhaust temperature curve is generated for each considered speed of the said low

pressure turbine.

6. Control method according to Claim 5, characterized in that an equation for evaluating the said current exhaust temperature TX is:

$$\begin{aligned} \text{TX} = & \text{TXbase}(\text{PCNLP}) + \text{DeltaTX\_DPin} + \text{DeltaTX\_DPout} \\ & + \text{DeltaTX\_Hum} \end{aligned}$$

where TXbase(PCNLP) is the reference temperature found for the said specific speed of the said low pressure turbine.

7. Control method according to Claim 6, characterized in that there are two values of TXbase(PCNLP), one related to a curve (21) of maximum temperature Tfire and one related to a curve (23) of maximum increase of temperature Trise of the gas in the combustion chamber.

8. Control method according to Claim 7, characterized in that the said two maximum values are, respectively,

$$\begin{aligned} \text{TX\_maxTfire} &= \text{TXbase\_maxTfire}(\text{PCNLP}, \text{PR}) + \\ &\text{DeltaTX\_DPin} + \text{DeltaTX\_Dpout} + \text{DeltaTX\_Hum} \\ \text{TX\_maxTrise} &= \text{TXbase\_maxTrise}(\text{PCNLP}, \text{PR}) + \\ &\text{DeltaTX\_DPin} + \text{DeltaTX\_Dpout} + \text{DeltaTX\_Hum}, \end{aligned}$$

where a dependence on the compression ratio PR is also expressed.

9. Control method according to Claim 8, characterized in that the said temperature curves TXbase\_maxTfire and TXbase\_maxTrise are provided in the form of two-dimensional tables, with the compression ratio PR and  
5 the low pressure turbine speed PCNLP as independent variables.

10. Control method according to Claim 8, characterized in that a diagram of the said maximum temperature TX, shown as a function of the compression ratio PR which  
10 enables the maximum Tfire to be attained, shows a set of curves (27), each for a specific value of speed PCNLP, the said curve (27) generally having an increasingly negative slope as this speed increases, and being always of the type decreasing with a rise in  
15 the compression ratio PR.

11. Control method according to Claim 8, characterized in that a diagram of the maximum temperature TX, shown as a function of the compression ratio PR, which  
enables the maximum Trise to be attained, shows a set  
20 of curves (29), each for a specific value of speed PCNLP, the said curve (29) generally having an increasingly negative slope as this speed increases, and being always of the type decreasing with a rise in the compression ratio PR.

12. Control method according to Claim 3, characterized in that the said correction DeltaTX\_Hum depends on the specific humidity SH and is expressed as a function of a difference DeltaSH, defined as the difference between the actual specific humidity and the specific humidity SH\_60%RH at a relative humidity RH of 60% (in the same conditions of temperature and atmospheric pressure), according to the formula:

$$\text{DeltaSH} = \text{SH\_current} - \text{SH\_60\%RH}.$$

10 13. Control method according to Claim 12, characterized in that there is a linear correlation (31) between the said DeltaTX\_Hum and the said DeltaSH.

14. Control method according to Claim 13, characterized in that the said humidity SH\_60%RH as a function of atmospheric temperature can be found by interpolating the following values, where the temperature is expressed in degrees Rankine:

$$\text{SH\_60\%RH (T=419.67)} = 0.000070;$$

$$\text{SH\_60\%RH (T=428.67)} = 0.000116;$$

20  $\text{SH\_60\%RH (T=437.67)} = 0.000188;$

$$\text{SH\_60\%RH (T=446.67)} = 0.000299;$$

$$\text{SH\_60\%RH (T=455.67)} = 0.000464;$$

SH\_60%RH (T=464.67) = 0.000707;  
SH\_60%RH (T=473.67) = 0.001059;  
SH\_60%RH (T=482.67) = 0.001560;  
SH\_60%RH (T=491.67) = 0.002263;  
5 SH\_60%RH (T=500.67) = 0.003324;  
SH\_60%RH (T=509.67) = 0.004657;  
SH\_60%RH (T=518.67) = 0.006367;  
SH\_60%RH (T=527.67) = 0.008670;  
SH\_60%RH (T=536.67) = 0.011790;  
10 SH\_60%RH (T=545.67) = 0.015966;  
SH\_60%RH (T=554.67) = 0.021456;  
SH\_60%RH (T=563.67) = 0.028552;  
SH\_60%RH (T=572.67) = 0.037585;  
SH\_60%RH (T=581.67) = 0.048949.

15 15. Control method according to Claim 3, characterized  
in that the said correction DeltaTX\_Dpin is expressed  
directly as a function of a measured pressure drop  
DPin.

16. Control method according to Claim 15,  
20 characterized in that there is a linear correlation  
(33) between DeltaTX\_Dpin and the said Dpin.

17. Control method according to Claim 3, characterized in that the said correction  $\Delta TX_{Dpout}$  is expressed directly as a function of a measured pressure drop  $DP_{out}$ .

5 18. Control method according to Claim 17, characterized in that there is a linear correlation (35) between the said  $\Delta TX_{Dpout}$  and the said  $DP_{out}$ .

19. Corrected parameter control method for a two-shaft gas turbine, characterized in that the control of the  
10 said turbine at partial loads is provided by a second control loop which controls the opening of a vent valve to keep the temperature rise  $Trise$  of the gas in the combustion chamber (and consequently the fuel-air ratio  $F/A$ ) within specified limits; the said control is  
15 provided by means of sets of maps of the exhaust temperature  $TX$  as a function of the compression ratio  $PR$ , obtained for each operating condition of the said gas turbine.

20. Control method according to Claim 19,  
20 characterized in that a control curve is defined for each value of atmospheric temperature.

21. Control method according to Claim 20, characterized in that there are diagrams showing the



relation between the said temperature TX, for partial loads at a given speed of the low pressure shaft, and the compression ratio PR, each relation curve (37) being associated with a specified value of atmospheric  
5 temperature, the said curve (37) generally having higher values as this temperature rises, and being of the type which decreases as the compression ratio PR decreases.

22. Control method according to Claim 21,  
10 characterized in that the said curves (37) are reduced to a single curve (39), thus eliminating the dependence on the atmospheric temperature.

23. Control method according to Claim 22,  
characterized in that the said curve (39) is obtained  
15 by the following mathematical transformation:

$$TTX = TX \cdot (518.67/TCD)^x$$

where

- TX is the actual exhaust temperature;
- 518.67 is a reference temperature;
- 20 - TCD is the exhaust temperature of the compressor, expressed in a unit of measurement compatible with that of the constant;
- X is a nondimensional exponent calculated in

such a way as to minimize the mean quadratic deviation between the values of TTX calculated in this way and the interpolation curve (39);

- TTX is the transformed exhaust temperature, in other words the reduced temperature.

24. Control method according to Claim 23, characterized in that the said curve (39), when the actual value of PR is known and after the application of the inverse of the said transformation, yields the reference temperature TXbase, from which the set point is calculated for the controller of the said second F/A control loop.

25. Control method according to Claim 24, characterized in that the said exhaust temperature TX is calculated by a linear approximation as the sum of the reference temperature TXbase to which are added corrections relating to a single environmental or operating parameter which differs from the reference parameter.

26. Control method according to Claim 25, characterized in that there are four of the said corrections, the said exhaust temperature TX being expressed by the following formula

$$\text{TX} = \text{TXbase} + \text{DeltaTX\_DPin} + \text{DeltaTX\_Dpout} + \text{DeltaTX\_Hum} + \text{DeltaTX\_PCNLP}$$

where

TXbase is found by inverting the said transformation,  
5 thus:  $\text{TXbase} = \text{TTX} / ((518.67/\text{TCD})^x)$ ;

DeltaTX\_Dpin is a correction of the temperature TX due to the variation of pressure drops in intake pipes with respect to a nominal value of 0 mmH2O;

DeltaTX\_Dpout is a correction of the temperature TX due  
10 to the variation of pressure drops in exhaust pipes with respect to a nominal value of 0 mmH2O;

DeltaTX\_Hum is a correction of the temperature TX due to the variation of relative humidity of the air with respect to a nominal value of 60%;

15 DeltaTX\_PCNLP is a correction of the temperature TX due to the variation of the low pressure shaft speed with respect to a nominal value of 100%.

27. Control method according to Claim 26,  
characterized in that each correction term is  
20 calculated by computer simulations of the gas turbine, the desired F/A ratio being specified, for each condition differing from the reference condition and at different partial loads, the said exhaust temperature

TX found by the said simulations being compared with the reference temperature TXbase, in order to evaluate the correction terms in the appropriate way as differences.

5 28. Control method according to Claim 27, characterized in that a set of curves (41), one for each given value of speed PCNLP, is shown in a diagram of the said maximum temperature TX as a function of the compression ratio PR.

10 29. Control method according to Claim 28, characterized in that an equation for evaluating the current exhaust temperature TX is:

$$\begin{aligned} TX = & TXbase(PCNLP) + DeltaTX\_DPin + DeltaTX\_Dpout \\ & + DeltaTX\_RH \end{aligned}$$

15 where TXbase(PCNLP) is the reference temperature found for the specific speed of the low pressure turbine.

30. Control method according to Claims 23 and 29, characterized in that the said exponent X is a function of the speed of the low pressure wheel.

20 31. Control method according to Claim 30, characterized in that the exponent X, for intermediate speeds PCNLP, can be calculated by interpolation of the values of X calculated at the speeds PCNLP considered:

if PCNLP = 105%, X = 0.323  
if PCNLP = 100%, X = 0.33225  
if PCNLP = 90%, X = 0.34  
if PCNLP = 80%, X = 0.34425  
5 if PCNLP = 70%, X = 0.351  
if PCNLP = 60%, X = 0.348  
if PCNLP = 50%, X = 0.3505.

32. Control method according to Claim 26,  
characterized in that the said correction DeltaTX\_RH is  
10 calculated by considering:

- three ambient temperatures (very cold day, ISO standard conditions, very hot day);
- three levels of relative humidity (0%, 60%, 100%);
- load characteristics according to a cubic law.

15 33. Control method according to Claim 32,  
characterized in that nine simulations are conducted,  
the desired value of F/A being specified, in order to  
achieve the reference level, the current values of TX  
then being plotted on a diagram as functions of PR,  
20 while a difference between the said diagram and the  
base curves yields the said DeltaTX\_RH, as expressed in  
the formula:

$$\text{DeltaTX\_RH} = \text{TX} - \text{TXbase}.$$

34. Control method according to Claim 33, characterized in that the said values of DeltaTX\_RH are plotted on the diagram as a function of the difference  
5 DeltaSH between the current value of specific humidity SH\_current and the specific humidity at RH = 60%, SH\_60%RH, which is the reference value, and thus

$$\text{DeltaSH} = \text{SH\_current} - \text{SH\_60\%RH}.$$

35. Control method according to Claim 34,  
10 characterized in that the said diagram shows two straight lines (43 and 45), rising with an increase in DeltaSH, in which a first straight line (43), valid where DeltaSH is less than 0, has a greater slope than the second straight line (45) which is valid where  
15 DeltaSH is greater than 0, the two straight lines (43 and 45) passing through a point near the origin of the axes.

36. Control method according to Claim 26, characterized in that the said correction DeltaTX\_Dpin  
20 is expressed directly as a function of the measured pressure drop DPin.

37. Control method according to Claim 36, characterized in that the following are considered:

- three ambient temperatures (very cold day, ISO standard conditions, very hot day);
  - three pressure drops in the intake (0, 100 and 200 mm of water);
- 5    -    load characteristics according to a cubic law.

38. Control method according to Claim 37, characterized in that nine simulations are conducted, the attainment of the desired value of F/A being specified, in order to achieve the reference level, the  
10    current values of TX then being plotted on a diagram as functions of PR, the difference between the said diagram and the base curves yielding the said DeltaTX\_Dpin, this being expressed in the formula

$$\text{DeltaTX\_Dpin} = \text{TX} - \text{TXbase}.$$

15    39. Control method according to Claim 38, characterized in that the said values of DeltaTX\_Dpin are linearly correlated (47) with the said Dpin, the said values increasing with a rise in Dpin.

40. Control method according to Claim 26,  
20    characterized in that the said correction DeltaTX\_Dpout is expressed directly as a function of the measured pressure drop DPout.

41. Control method according to Claim 40,

characterized in that the following are considered:

- three ambient temperatures (very cold day, ISO standard conditions, very hot day);
- three pressure drops in the exhaust (0, 100 and  
5 200 mm of water);
- load characteristics according to a cubic law.

42. Control method according to Claim 41, characterized in that nine simulations are conducted, the attainment of the desired value of F/A being  
10 specified, in order to achieve the reference level, the current values of TX then being plotted on a diagram as functions of PR, a difference between the said diagram and the base curves yielding the said DeltaTX\_Dpout, as expressed in the formula:

$$15 \quad \text{DeltaTX\_Dpout} = \text{TX} - \text{TXbase.}$$

43. Control method according to Claim 42, characterized in that the said values of DeltaTX\_Dpout are linearly correlated (47) with the said Dpout, the said values increasing with a rise in Dpout.

20 44. Control method according to Claims 35, 39 and 43, characterized in that a correlation for calculating the maximum exhaust temperature TX is:

$$\text{TX} = \text{TTX}(\text{PCNLP}, \text{PR}) / ((518.67/\text{TCD})^{\text{X}(\text{PCNLP})}) +$$



DeltaTX\_RH (DeltaSH) +

DeltaTX\_Dpin (Dpin) +

DeltaTX\_Dpout (Dpout).

45. Control method according to Claim 1 or 19,  
5 characterized in that the said two-shaft gas turbine is  
provided with a dry nitrogen oxide (NOx) reduction  
system.

Fig.1

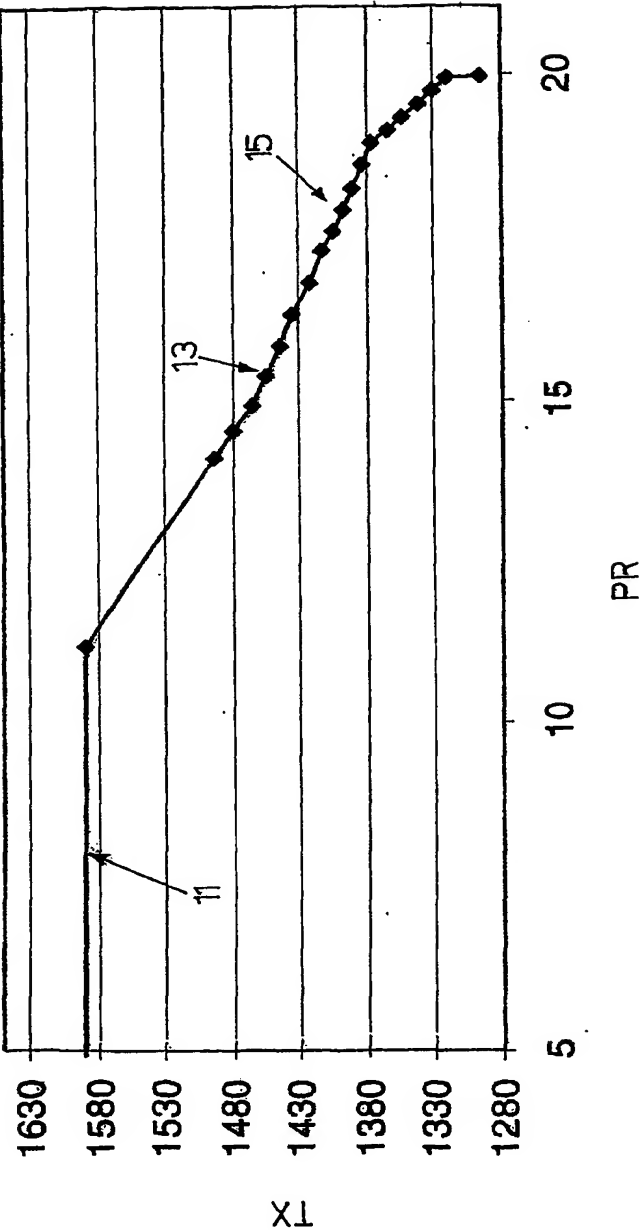
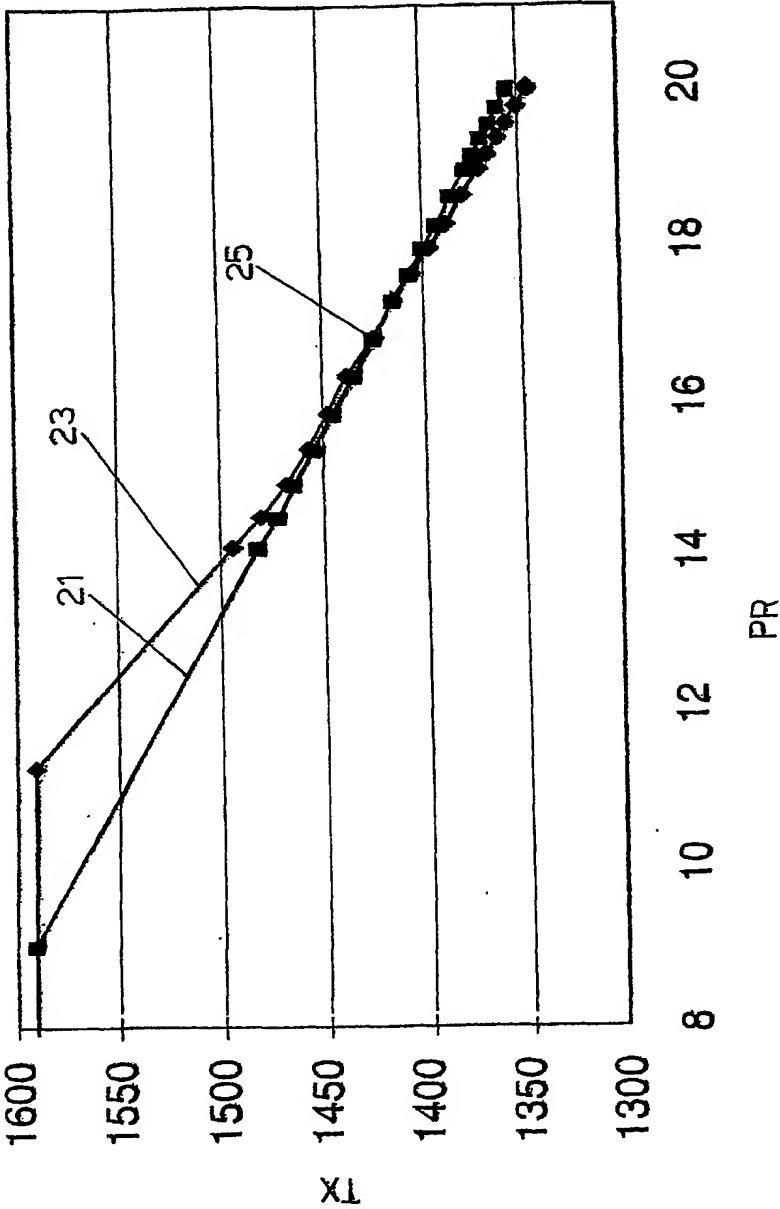


Fig. 2



**Fig. 3**

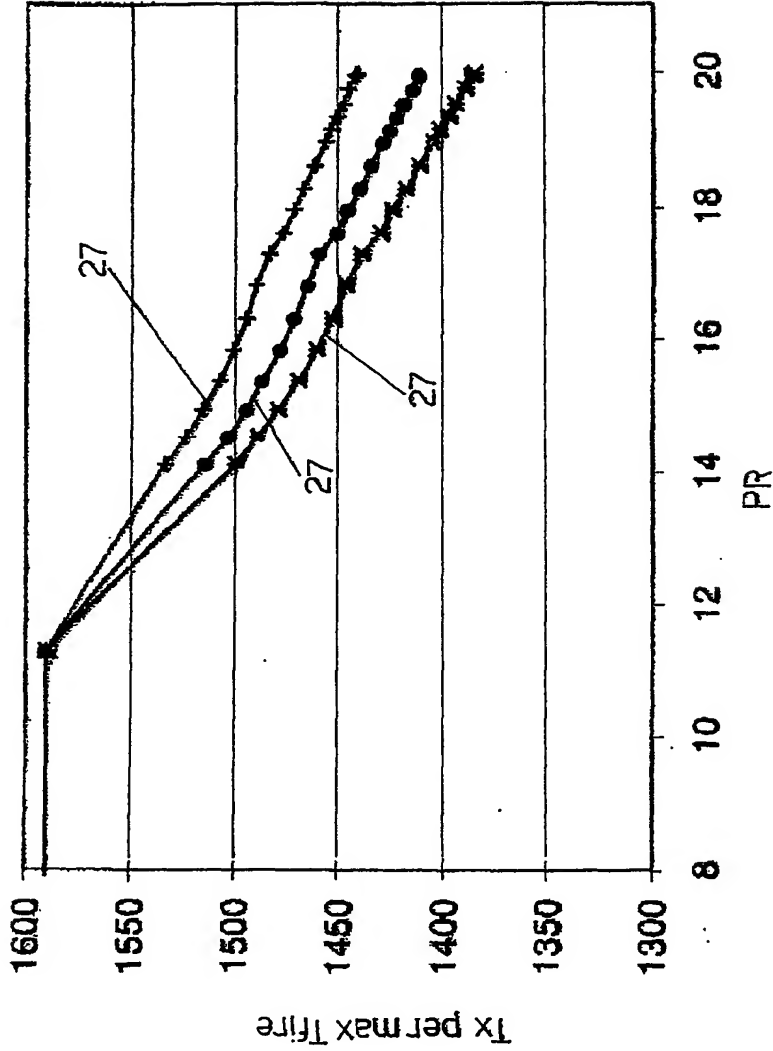
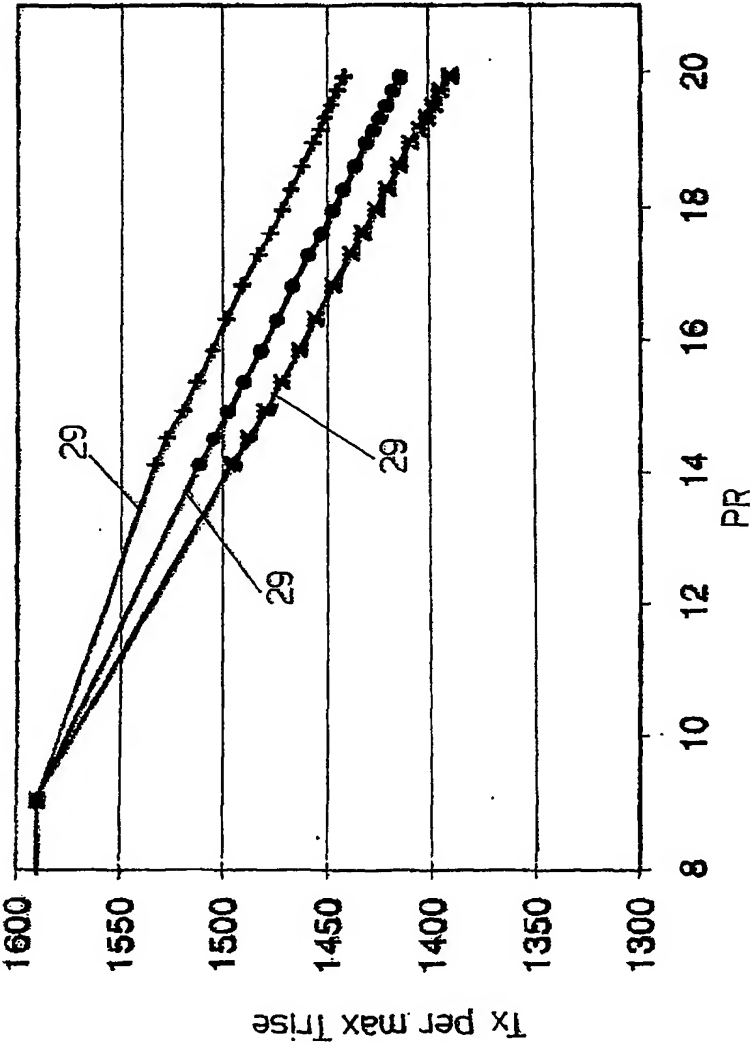
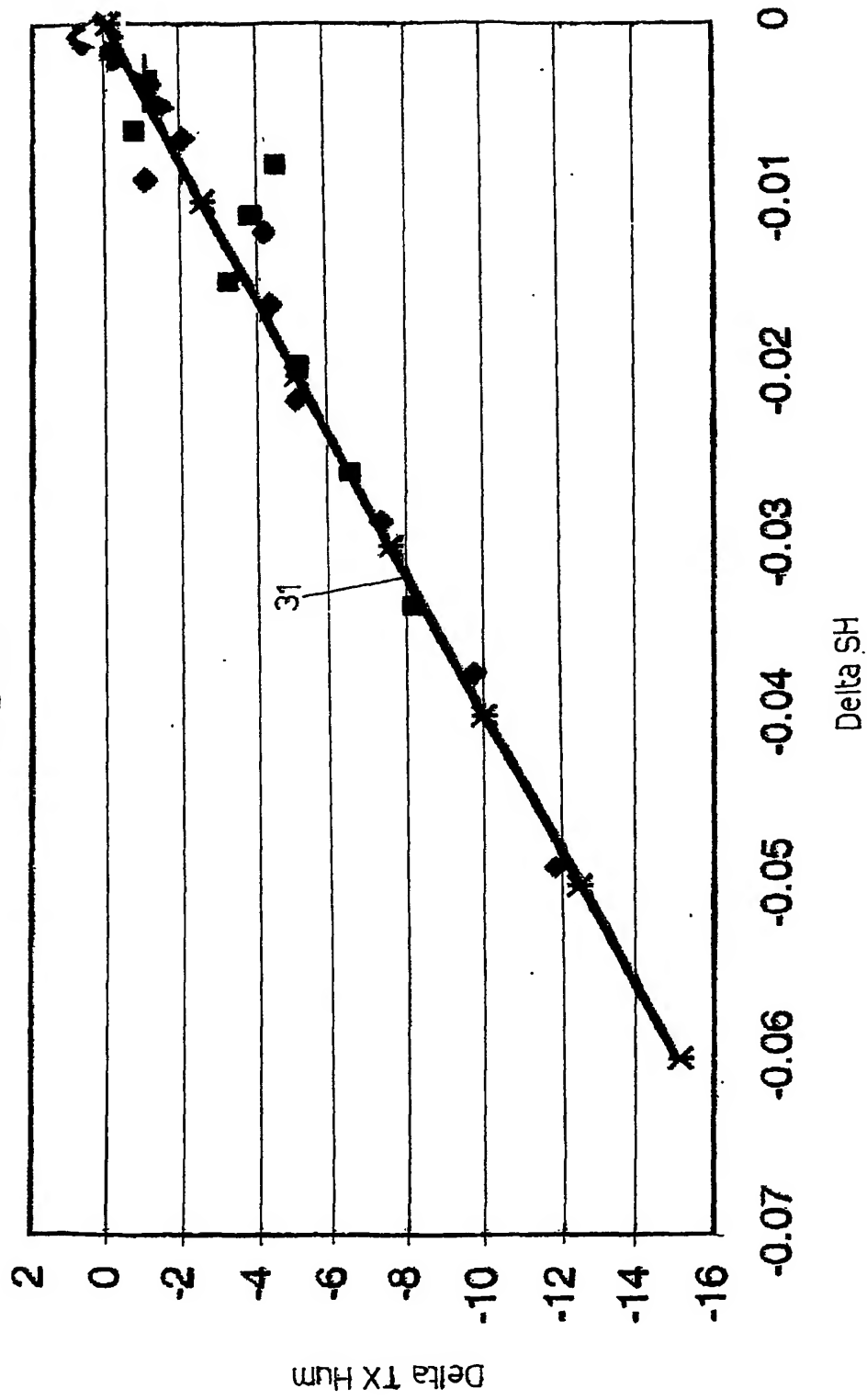


Fig. 4



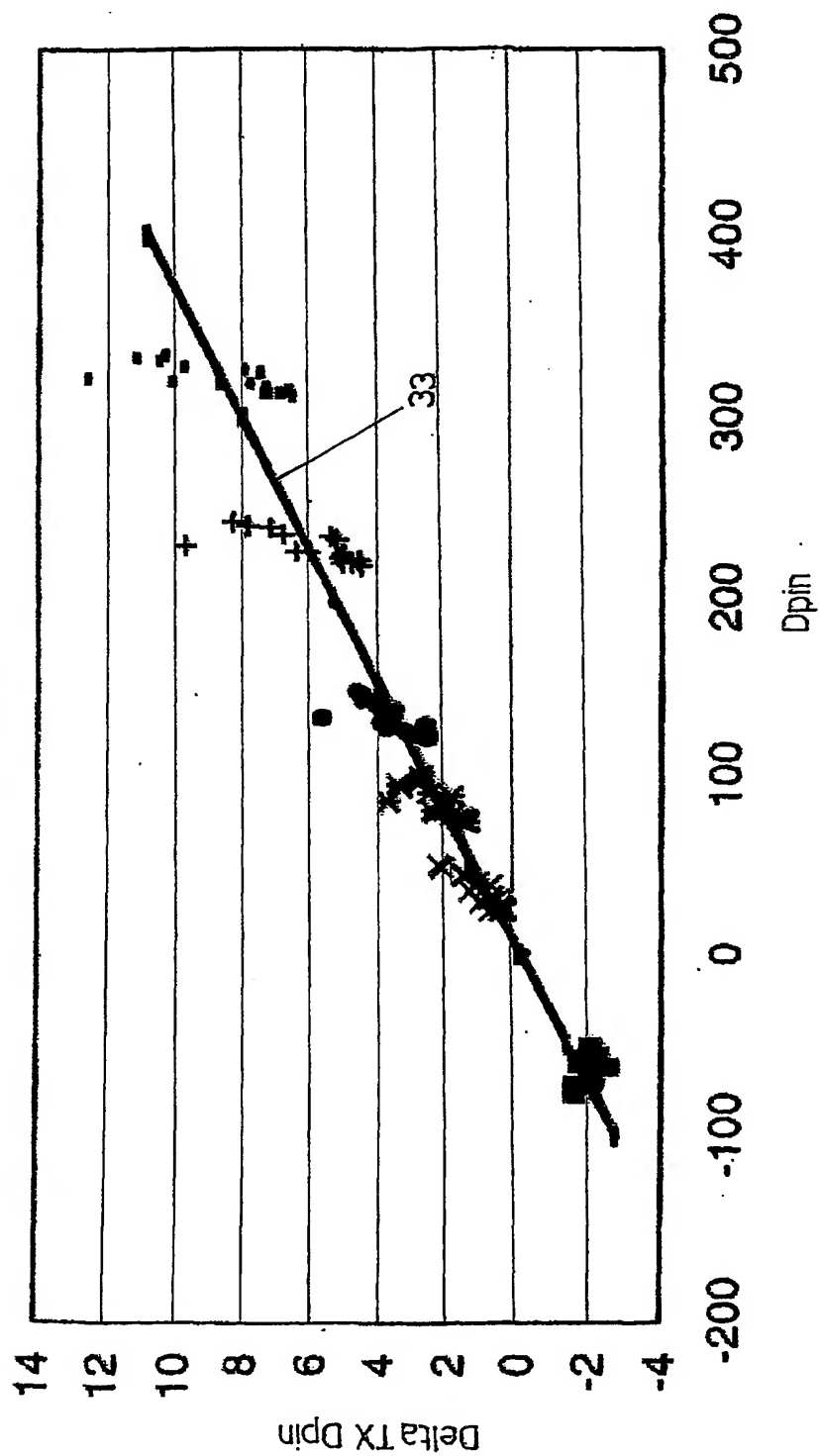
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Fig. 5



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Fig. 6



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Fig. 7

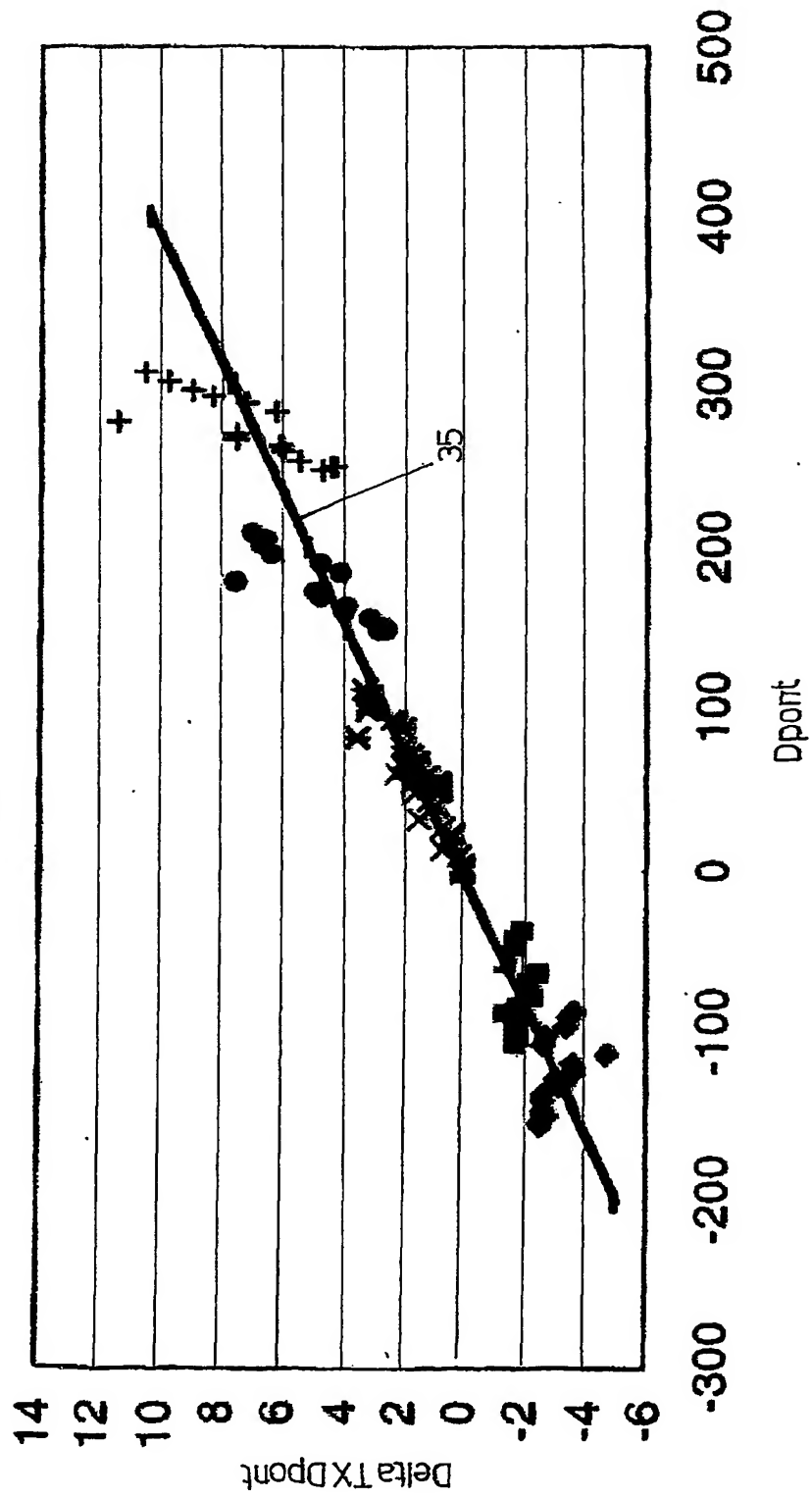
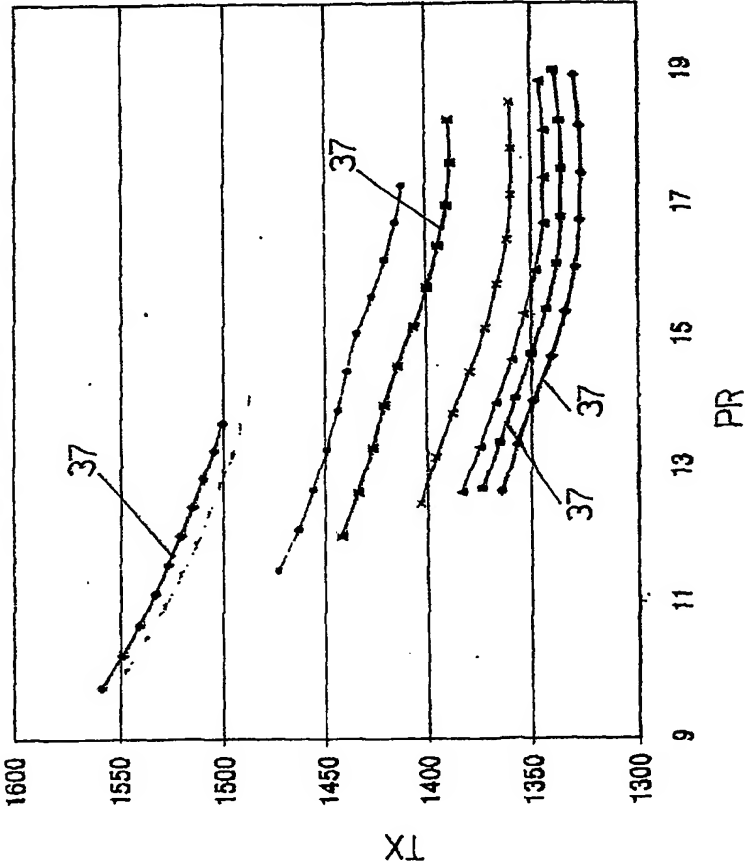
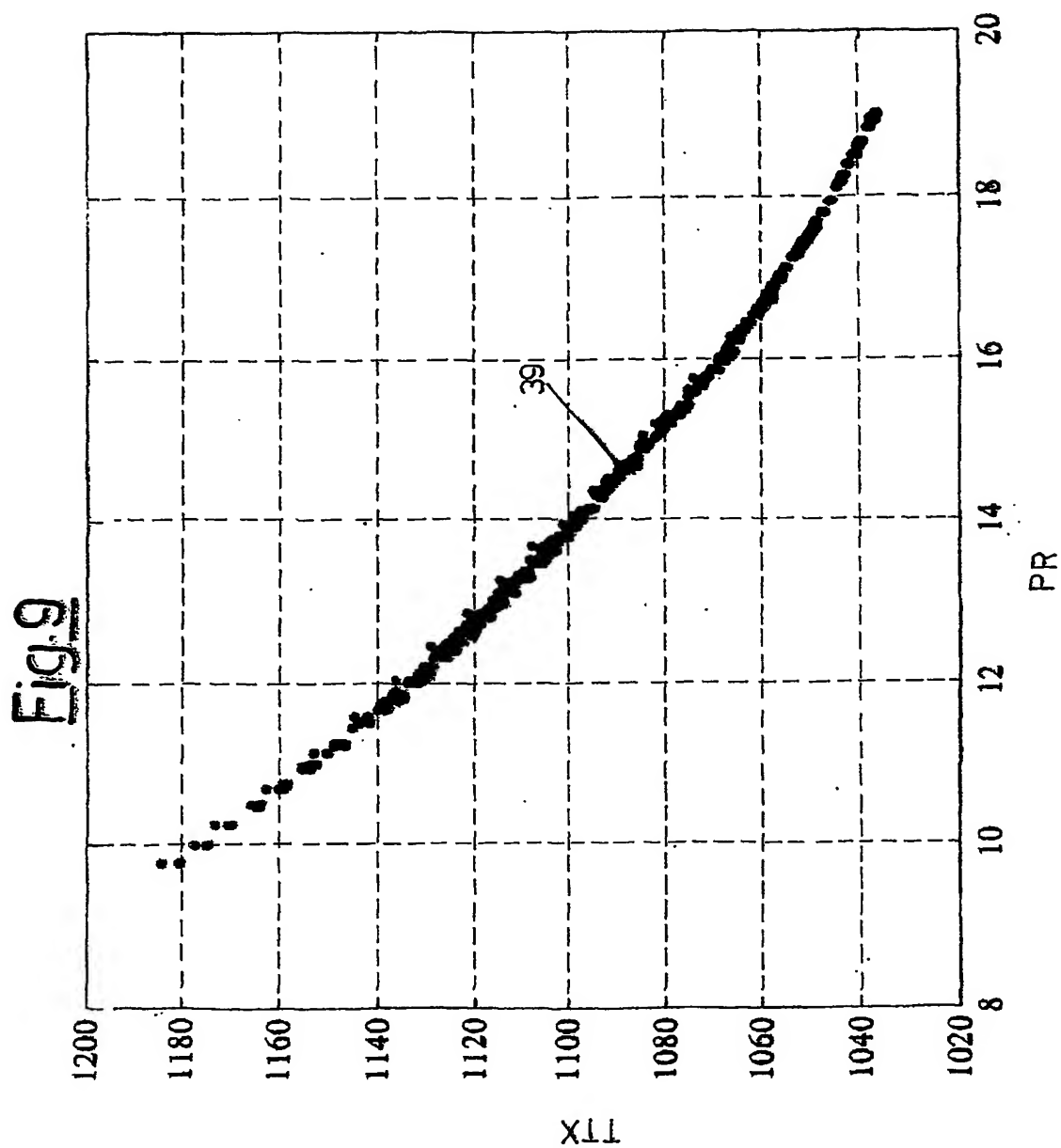




Fig. 8

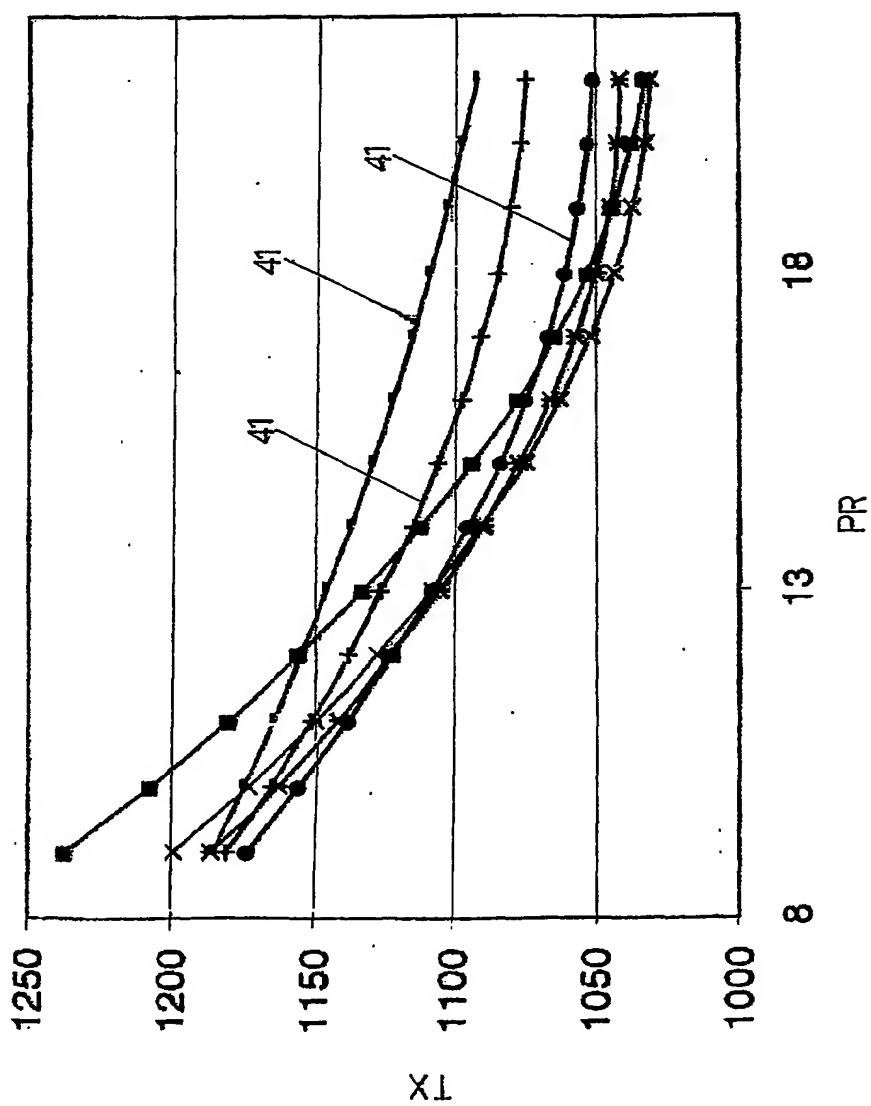


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Fig.10



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Fig.11

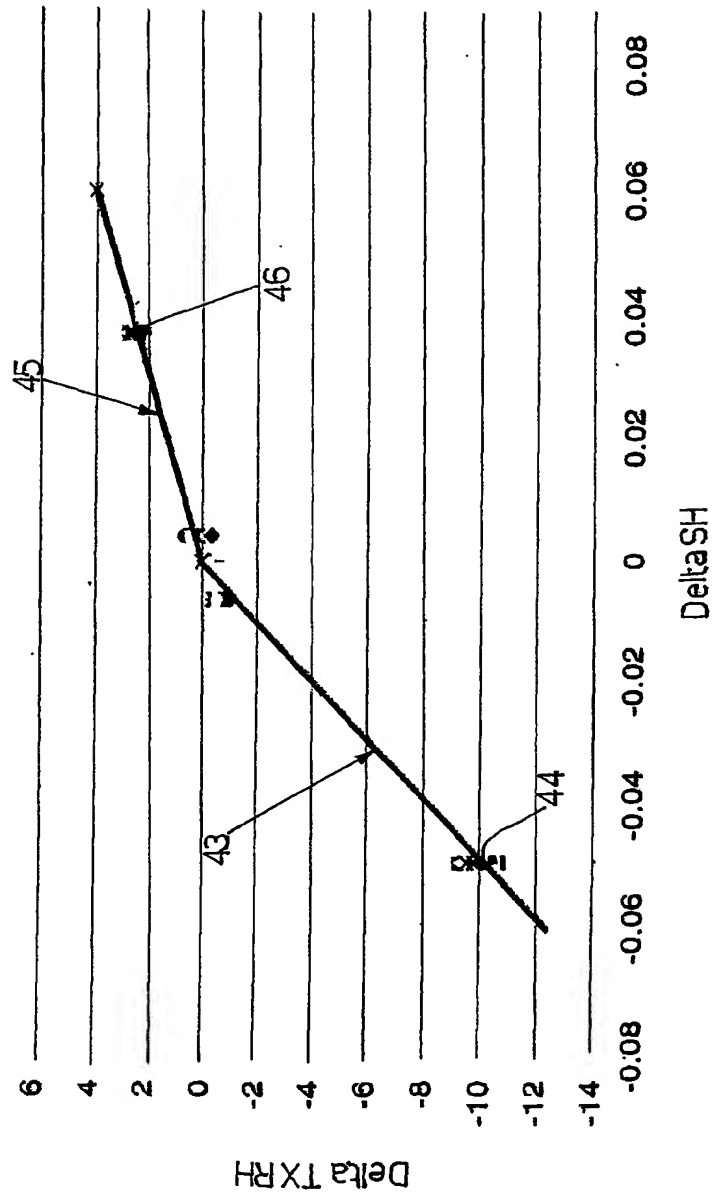


Fig.12

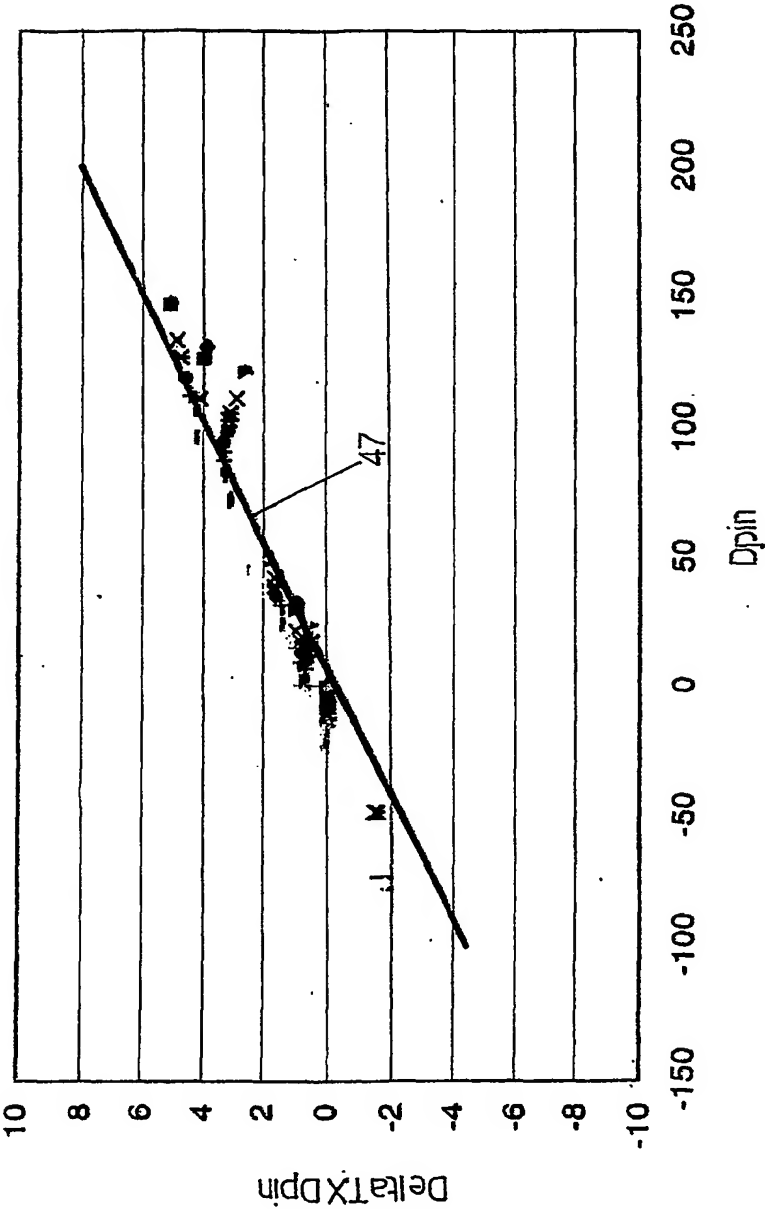
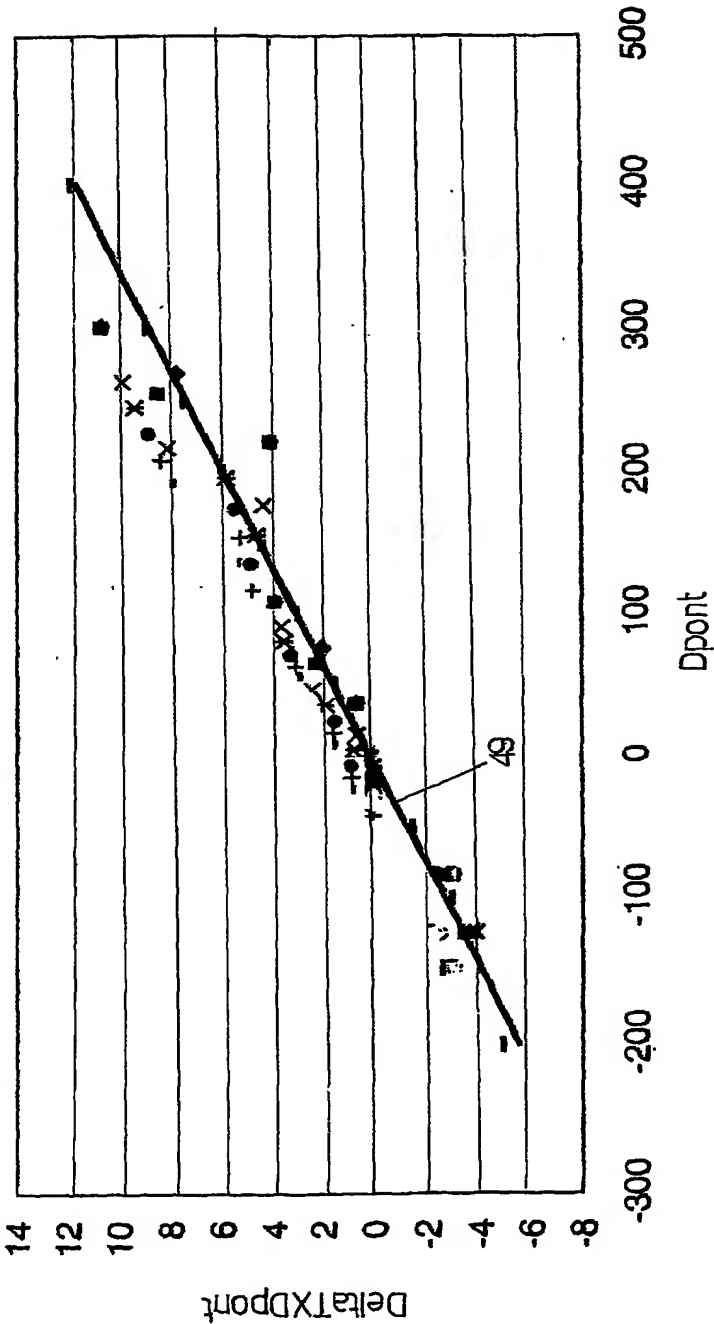


Fig.13



## INTERNATIONAL SEARCH REPORT

International Application No  
PCT/EP 03/14174

A. CLASSIFICATION OF SUBJECT MATTER  
IPC 7 F02C9/28 F01D21/12

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)  
IPC 7 F02C F01D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the International search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 728 919 A (COMPRESSOR CONTROLS CORP) 28 August 1996 (1996-08-28) page 1, line 16 -page 1, line 56 ---	1,2
X	US 4 809 497 A (SCHUH PAUL A) 7 March 1989 (1989-03-07) column 2, line 5 -column 2, line 18 column 4, line 41 -column 6, line 31; figure 6 ---	1,2
X	EP 1 231 369 A (GEN ELECTRIC) 14 August 2002 (2002-08-14) column 1, line 27 -column 2, line 39 column 7, line 29 -column 9, line 8; figure 1 --- -/--	1,2

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search

17 May 2004

Date of mailing of the international search report

28/05/2004

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# INTERNATIONAL SEARCH REPORT

International Application No  
PCT/EP 03/14174

## C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	<p>US 4 314 441 A (YANNONE ROBERT A ET AL)            9 February 1982 (1982-02-09)            column 4, line 64 -column 5, line 27            column 12, line 7 -column 14, line 42;            figure 5</p> <p style="text-align: center;">-----</p>	1



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US 4314441	A	09-02-1982	NONE	

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